Static liner Spice models of Atlas

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Introduction and circuit description

This report summarizes some of the results of Atlas circuit simulations for the oil filled vertical triplate transmission line (VTL), using Spice. The main circuits used are called oil4trn and oil4simp, and are run under Ispice4 from Intusoft. [1] The model oil4trn uses an approximation to the VTL of a 6 segment LC circuit. [2] This circuit is designed as a worst case estimate for the effect of the transmission line in terms of voltage oscillation due to the line inductance and capacitance. The segmented circuit uses a resistor in series with the capacitance of the cells to critically damped the cell oscillation. This is done in order to not violently over-estimate the oscillation, while still allowing transient response in the line, beyond that which a simple inductance in series with the bank would produce. Oil4simp uses a simple inductance equivalent to the 6 segments. The intention of the two models is to provide a tool for assessing peak current, the parasitic effect of incorrect switch firing, capacitor voltage reversal, power supply response to the Marx erection, and any other effect that might become a concern during the design phase of the Atlas machine. The models can be used to analyze the effect of jitter and unmatched submaster firing times in the trigger system and railgaps. Having both a simple inductance and a worst case LC segment model allows limits to be placed on voltage stress felt in various locations due to parasitics and reflected energy returning to the Marx banks from the load in the event of mistimed switches. This set of models is not intended to replace the modeling done by Gribble using the SCAT code, but rather augment it with similar models using different switch characteristics. The package produces circuit diagrams for self-documentation which are unavailable for SCAT models unless drawn by hand. As such, these models act as a cross check on the SCAT modeling. The models are available upon request for use by anyone having a compatible Spice simulator. The behavioral modeling done for the switches may provide a difficulty for users with packages written by other vendors.

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[1] These models include the vertical transmission line but will be superseded by other models as the detailed circuit parameters evolve, and eventually will be replaced by a set of models including liner dynamics.

[2] Attempts to utilize cascaded ideal or lossy transmission lines from the Ispice4 package were unsuccessful due to numerical instability that could not be defeated despite concerted efforts. One should keep in mind the fact that a discrete undamped LC model always produces more severe ringing than an ideal line, and thus presents the worst case estimate. The critically damped version gives an oscillation slightly larger that Gribble's ideal line model. Without the damping, the segmented model exceeds Gribble's ideal result by 20%.

In addition to the VTL models, each circuit has a simple inductance for the transition section between the transmission line and the diskline that connects to the implosion liner. The net oil VTL inductance was 2.785 nH based on the formulas for a 7.7 m long, tapered (from 6' to 2') transmission line with a 1" oil filled triplate gap. The transition inductance was 1.6 nH, based on the final presentation vugraphs from the transmission line working group [3]. The railgaps are broken into a long and short section, with 13 nH and 7 nH inductance, respectively. The capacitance of the railgap is included, with 10 pf and 20 pf values in the two sections. The railgap switch model used is a simple exponential drop in switch resistance with a variable e-folding time, typically set to 2.5 ns, which produces a current rise in the switch that rises to maximum in 30-40 ns[4]. Each switch can be set to fire at an independently controlled time, as can each half of a particular railgap. (Single channels are modeled by replacing the net 20 nH railgap inductance for normal operation with an 80 nH inductance, partitioned into two parts as in the normal case.) The series resistor is the 228 mΩ tentatively discussed to allow reduced voltage operation within the reversal specification on the capacitors. The output cables are included for each Marx as an additional 62 nH (14 11' RG-218 cables, labeled LCONa in the A1 Marx circuit diagram). The circuit includes the trigger system to realistically estimate the amount of circulating current in the trigger cables (typically < 2 kA oscillating). The trigger circuit is a dump line as in the real system but only uses a single switch with a single bypass capacitance, rather than the more complicated two gap model used in some recent work by Gribble. Four individual Marx circuits (A1-4) contain a complete single trigger system and module interconnects, railgap stray capacitances, and all major parasitics. This set of 4 Marx modules drives one VTL. The remainder of the circuit consists of two 74 Marx equivalents to drive the final load assembly to the full system level. Constructing various levels of detail allows complete analysis of fault modes in the detailed sections while retaining a small simulation environment for rapid calculation. The separation of the balance of the driver into two 74 Marx equivalents allows an analysis of the effect on the circuit of having half the machine misfire due to a fault or an intentional misfiring to produce a foot on the drive pulse. The major component values are shown in Table 1.

[3] Both values will be updated when Flux3D calculations for the engineering design are done.

[4] This is a model which does not contain the physics of the resistive phase described by Tom Martin, which is used in Robin Gribble's more extensive SCAT models. Comparison of the results from this set of models and SCAT models suggest the difference is at most a few % for most of the items of interest in these studies. The two sets of models are cross checked against each other frequently, to maintain consistency in the circuit assumptions and check the simulation integrity.

Circuit element	value (single Marx, 152 ea.)	single circuit equivalent
Series R	228 mΩ	1.5 mΩ
Capacitance (each)	33 ufd (4 each)	1254 ufd
Cap inductance	16 nH (4 each)	0.21 nH
Railgap inductance (MC)	20 nH (2 each)	0.26 nH
Cable inductance	62 nH	0.41 nH
VTL inductance	423.32 nH (split 4 ways)	2.785 nH
Transition inductance	243.2 nH (split 4 ways)	1.6 nH
Diskline inductance	577.6 nH	3.8 nH
Static liner inductance	152 nH	1 nH
Parasitic inductances	80 nH	0.53 nH

The circuit diagram is broken into multiple pages as shown in the Appendix. The values used in the detailed Marx, and the associated lumped inductances in the 74 Marx equivalent, are values arrived at in conjunction with Gribble. The capacitors are assumed to be 33 ufd with an inductance of 16 nH (labeled LCxx in the A1 Marx circuit diagram). This inductance is in fair agreement with the most recent set of ring down data from the Atlas testbay, and has removed from it the inductance felt in the return circuit between the capacitors that is included in the parasitic transmission line model. (See the components labeled LHL and CHL in the A1 Marx circuit.) The railgaps have a 20 nH series inductance (LGAPxx) in agreement with the Maxwell specification and Atlas testbay currents. The component labeled LCONx is the inductance due to cables from the Marx header to the VTL, as well as any inductance (assumed essentially zero here) due to the disconnect switch. The series resistor (RSDMPx) is set to 228 mΩ. The shunt resistance and inductance is set to 5 Ω and 70 nH respectively. The parasitic labeled LVLxx is the return parasitic for the backplane where the series resister and cable header is located. The final load in all cases is comprised of the 3.8 nH inductance due to the diskline and conical section of the PFC and the 1 nH static liner. All these values are common to Gribble's SCAT model. A model will be created at a later date to include the dynamic inductance and resistance of the imploding liner, in a self consistent manner.

Baseline results

Two load current waveforms are shown in Figure 1 for operation at 50 and 60 kV charge voltage. The two models (simple inductance and resistively damped segments) show differences in the current waveform only in the earliest portion of the current rise as an oscillation of at most a couple of percent of the peak current due to the presence of the LC segments, even in the worst case where the VTL RLC loss resistance is set to zero ohms. In the normal critically damped case the oscillation in the current waveform is essentially invisible unless the leading edge of the current waveform is blown way up to display the first few MA of current. In both models, the 4.8 nH static load produces a net current of about 54.8 MA at 60 kV charge**.** Note that with this static load the total capacitor reversal is unacceptably large. (The reversal is 15.6 kV out of 60 kV charge, for a net reversal of about 25%. This is the reason for looking at operation at 50 kV

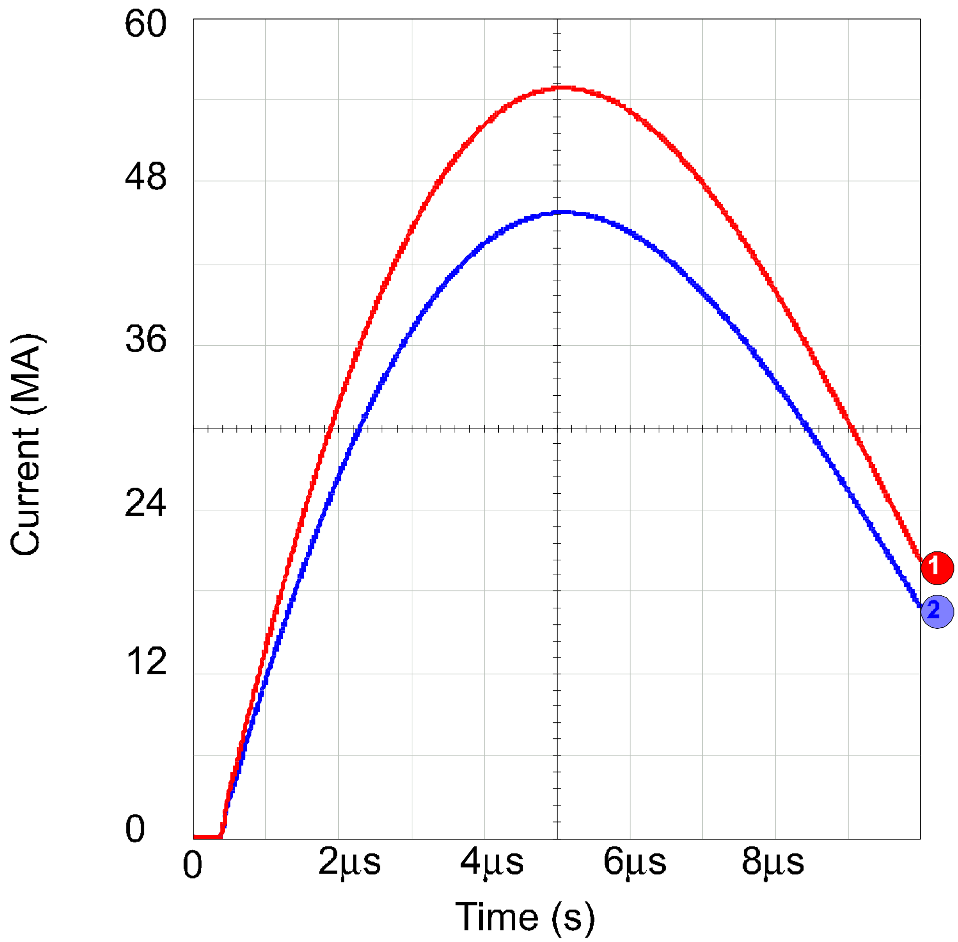


Figure 1. Liner current for 6 segment model at 50 and 60 kV charge voltage.

charge with the current 1.5 mΩ equivalent circuit series resistance.) This reversal will be subdued significantly by the real dynamic liner, because the final current will be reduced at the expense of larger coulomb transfer. The voltages felt at the liner are 22 kV for the simple inductance, and 34 kV at the oscillation peak for the critically damped 6 segment model.

The switches are fired at 300 ns in these calculations. Total charge transfer per switch into a static liner load is about 3.6 coulombs by the time of the second current zero crossing, if the ringing gets that far before a crowbar occurs in the power flow channel. Current and Q in the absence of any crowbar mechanism are shown in Figure 2.

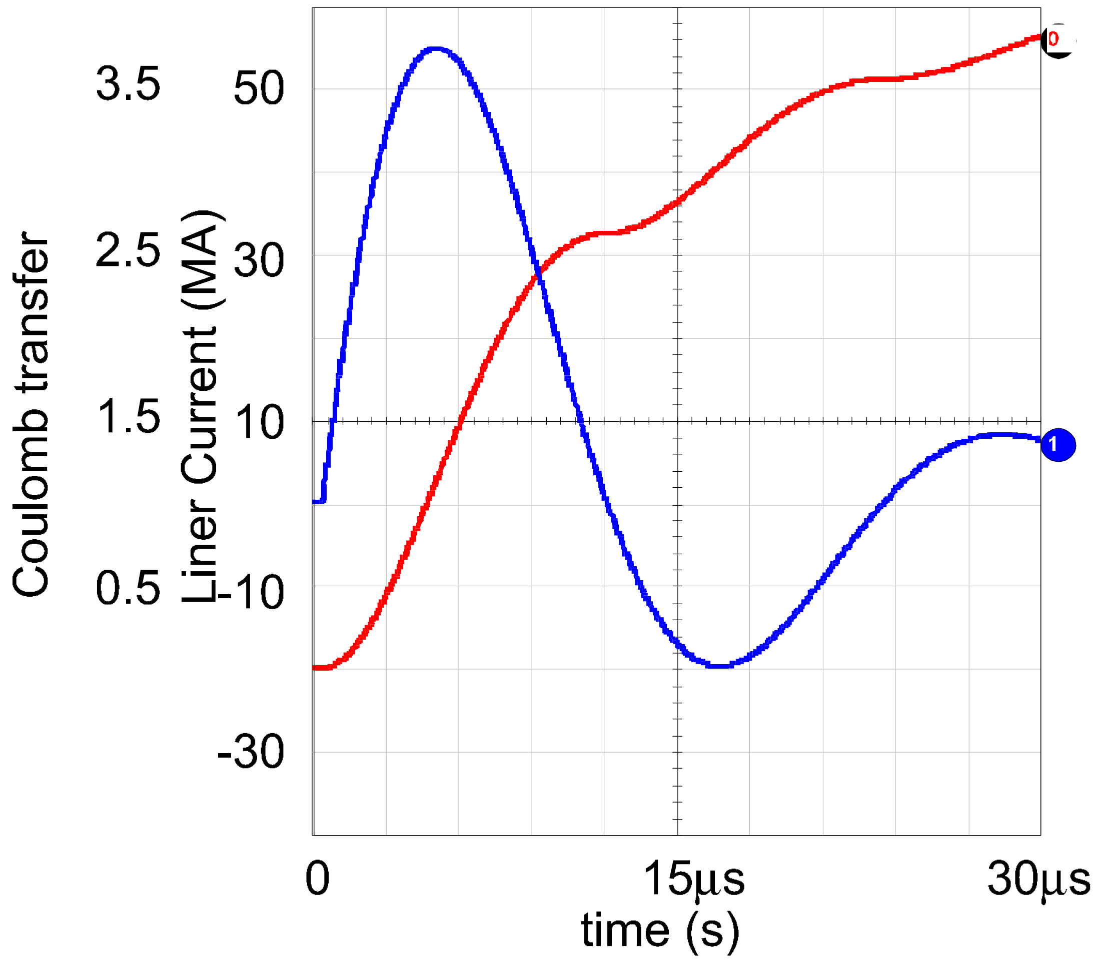


Figure 2 Charge transfer into a static 4.8nH load, in the absence of any crowbar mechanism.

Of concern in the system analysis is the intra-Marx parasitic voltage level felt in normal operation. The worst parasitic voltage is felt from capacitor to capacitor in a particular stage of the Marx. In the oil insulated VTL machine the voltage felt between capacitors in a single stage of the Marx is somewhat dependent on the ringing due to the VTL model. As shown in Figure 3 the penalty due to the discrete model is minor, even in the non-damped case shown, resulting in an increase of only around 10% over the simple inductor. As will be discussed in a separate fault analysis to be written later, a much larger parasitic excursion is caused when one of the railgaps in a Marx is mistimed relative to the other by times exceeding 20 ns or so. In that case the parasitic voltage can double, becoming a real concern and leading to a specification for the gap-gap delay of less than 10 ns 3σ.

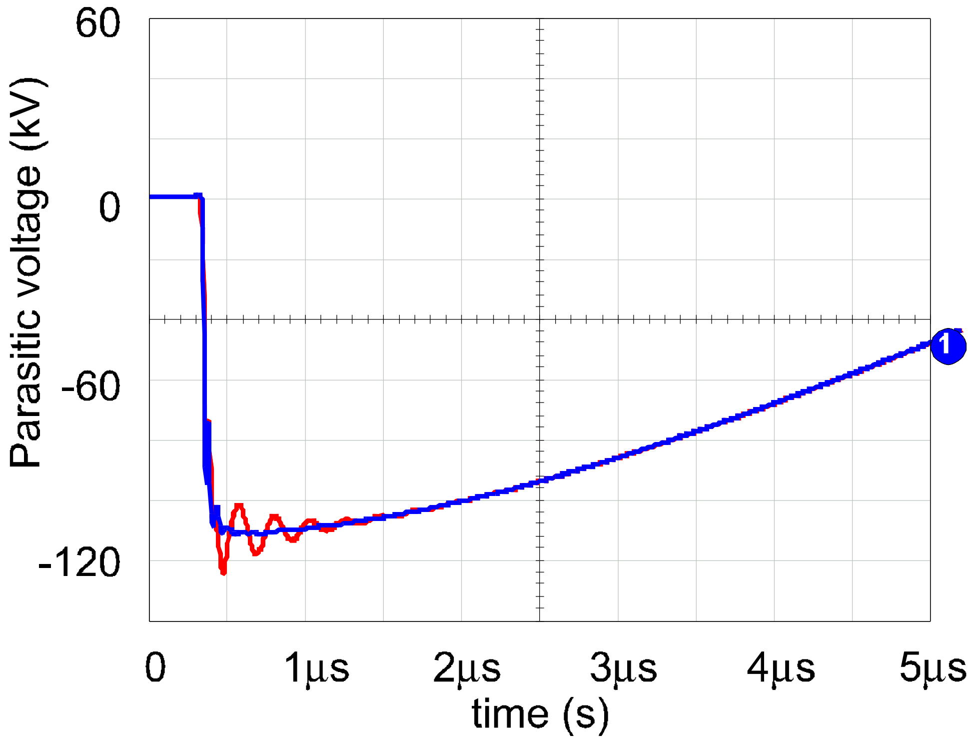


Figure 3 Capacitor to capacitor parasitic voltage for the simple inductor and undamped 6 segment model.

A second item of concern is the voltage ringing felt inside the VTL. Prudence dictates using a conservative estimate for the voltage levels in the VTL, such as is produced by the segmented model, in the triplate design effort. Figure 4 compares the midline voltage levels for the simple and segmented models, including a dotted curve for the undamped triplate oscillation, an intermediate excursion curve for the critically damped version, and the smallest excursion case for the simple inductor. The maximum excursion under normal conditions will probably not be as large as the 270 kV during the oscillation peak seen in the undamped 6 segment simulation, but is very likely at least equal to the critically damped 210 kV level. Design of the oil gap should probably use this figure rather than the figure of 170 kV from the simple model, given the lack of certainty about surface area and discharge time scaling for the oil breakdown voltage.

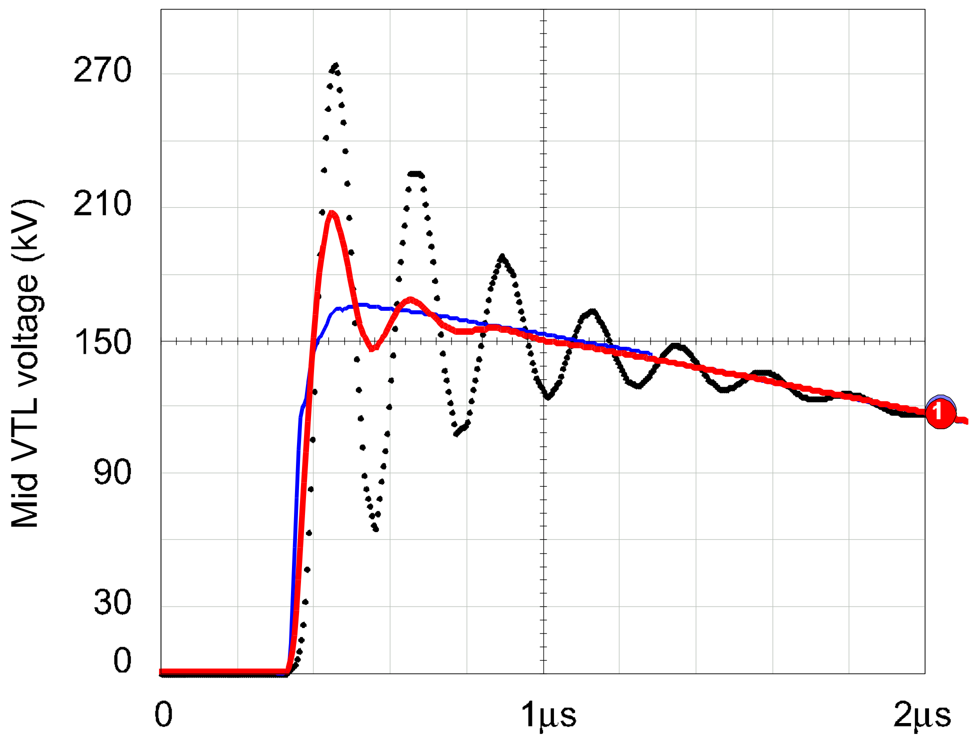


Figure 4 Voltage felt in the middle of the vertical triplate transmission line. The dotted curve is the undamped 6 segment model. The smooth curve is the simple inductor, and the thicker, intermediate curve is the more realistic critically damped 6 segment model.

Finally, the voltage and current levels in the trigger system are a concern because the present plan calls for a single submaster firing all the railgaps in a maintenance unit. The model includes a single submaster connected to Marx units in the detailed Marx sections to address this issue. The units are isolated from the trigger switch by 0.57 nfd capacitance (3 series 1.72 nfd BaTi capacitors on the center conductor and shield of each cable). In addition, each cable is wound into a coil of about 5 µH equivalent inductance for common mode voltage bucking. That inductor, while present in the model, is currently set down to a 5 nH value with no adverse effects on circulating current. The voltage excursion of the common shields, the voltage felt across the isolation caps, and the net circulating current in the cables are all a concern. As shown in Figure 5, a peak oscillating current of order 1.5 kA will be present for a given Marx in each of the trigger system outer conductor braids, and the maximum excursions of the isolation cap voltage should be of order +/- 80 kV in the absence of faults. Both of these numbers are easily accommodated by two sets of capacitors on each cable (shield and center conductor), both with three BaTi capacitors in series. Those capacitors are rated at 50 kV DC and tested to 60 kV, so three in series on each side is far within the breakdown specification. The common side of the shields jump to around 100 kV, with 20% oscillations, when the Marx fires in normal operation. The railgap ends of the shields go to around 50 and 150 kV in the two stages of a Marx, so standoff between the two cables must be insured to avoid breakdown between the PVC outside coatings. With judicious spacing between the cable routings, and with the trigger cables enclosed in separate PVC tubing as in the prototype Marx module, the trigger system can probably survive the transients. No DC current in the cables is present since both of the railgaps sit at -60 kV prior to firing.

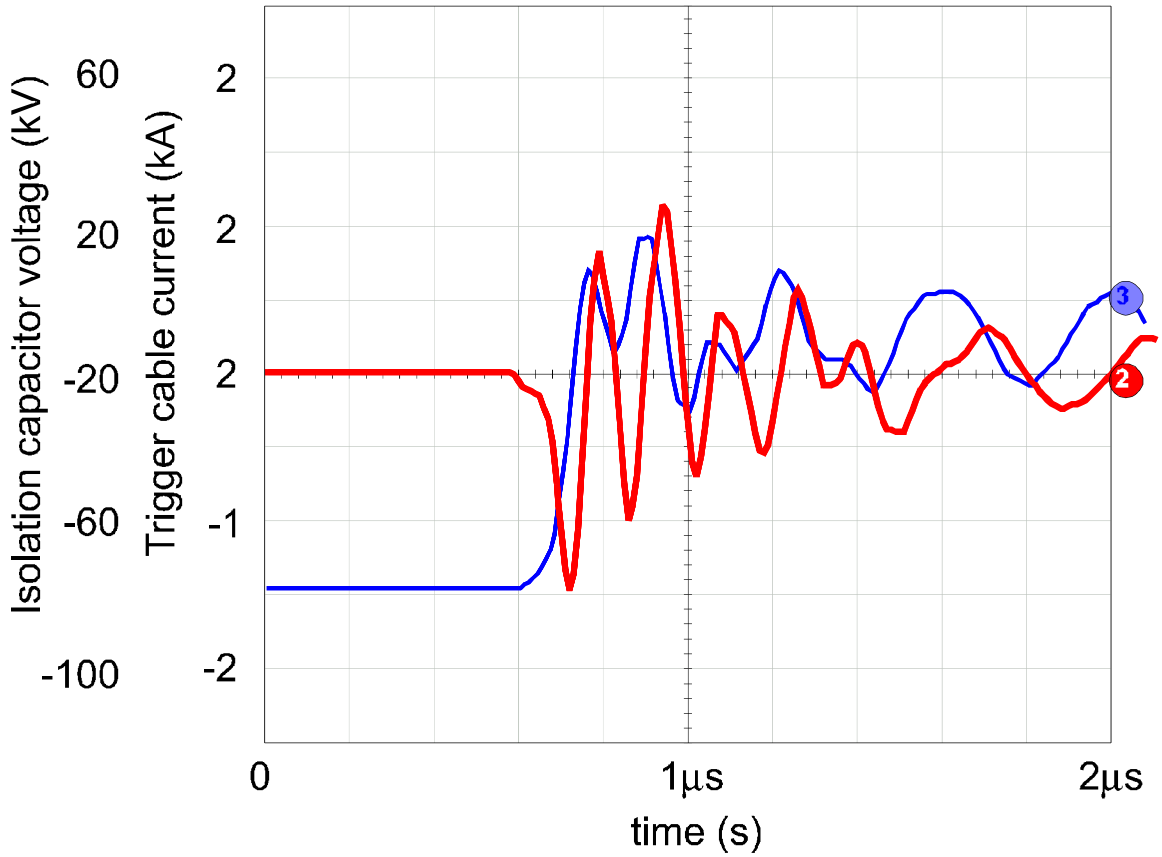
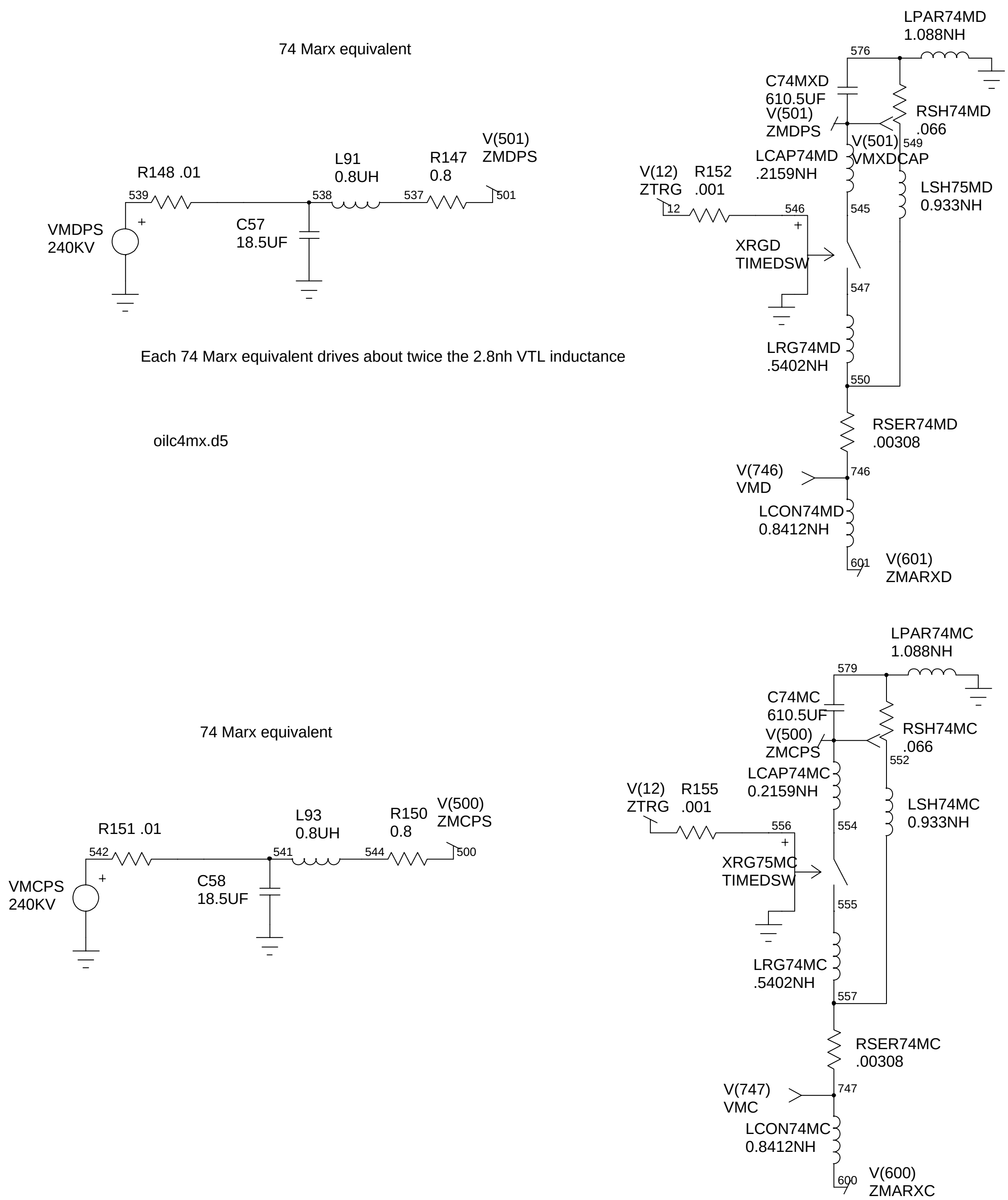


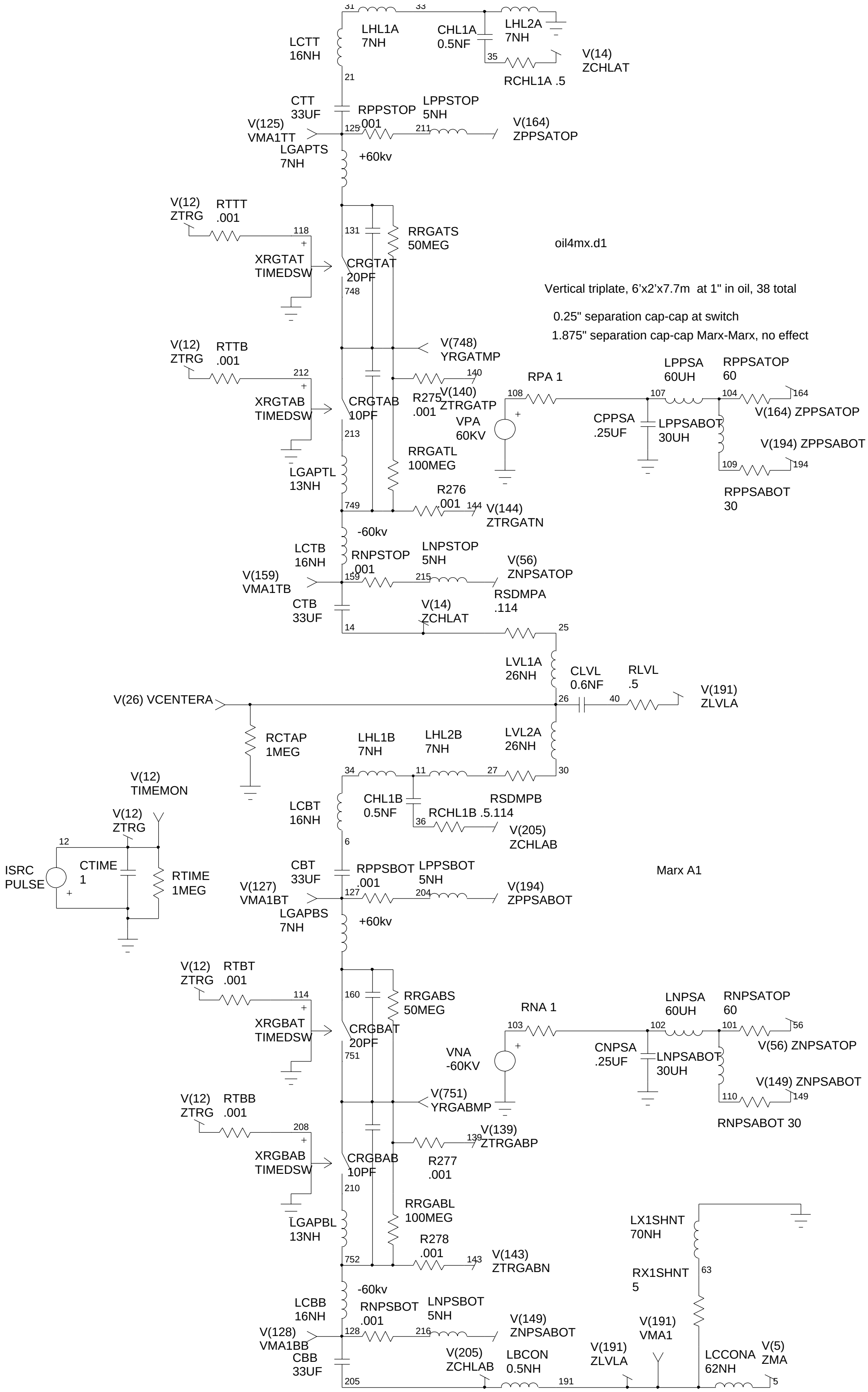
Figure 5 Capacitor transient voltage and circulating current in the trigger system shields during normal operation of the Marx units.

Appendix: circuit schematics.

Four of the seven schematic sheets are shown below. Four detailed Marx circuits similar to Marx A1 are present in the full model. The balance of the driver is shown in sheet 5. Power supplies are shown for all banks to enable correct simulation biasing at time zero in Spice, and to allow one to assess circulating currents in the supply lines. Additionally, the power supply in the trigger circuit is floated to allow accurate evaluation of the shield voltage level during a shot. The reversal diodes in the various Marx charging configurations have been left out of the diagrams, as shown, but when those diodes are placed in the anticipated position, the correct clamping effect is observed. Final details of the charging supply resisters, capacitors, and inductors are not yet settled. The 60 and 30 Ω values shown come from early discussions with Reass and may change based on the prototype results. The trigger system is presently constructed as in the prototype Marx, with capacitors on both sides and not connected to the charge resisters. That is a another variation that may change in the future.



Sheet 5. This schematic contains the balance of the driver (oil4mx.d5)



Sheet 1. Detailed Marx configuration (oil4mx.d1)

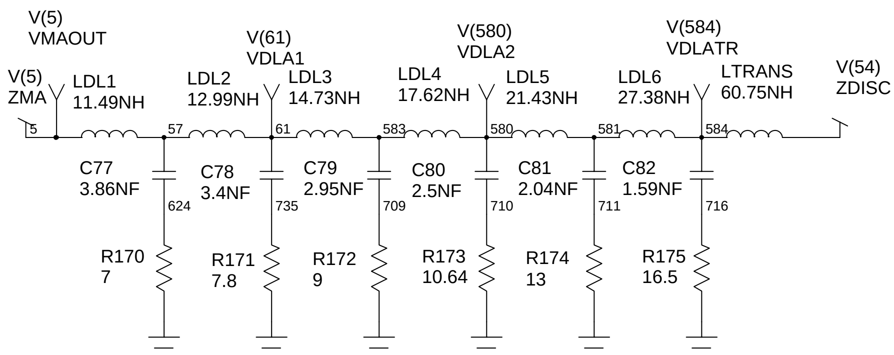
oil VTL modeled at 6 equal length segments, 6' to 2', 1 " spacing, 7.7m total

transition section 1.6nh per review spec.

Total VTL inductance, 2.785nh oil4mx.d2

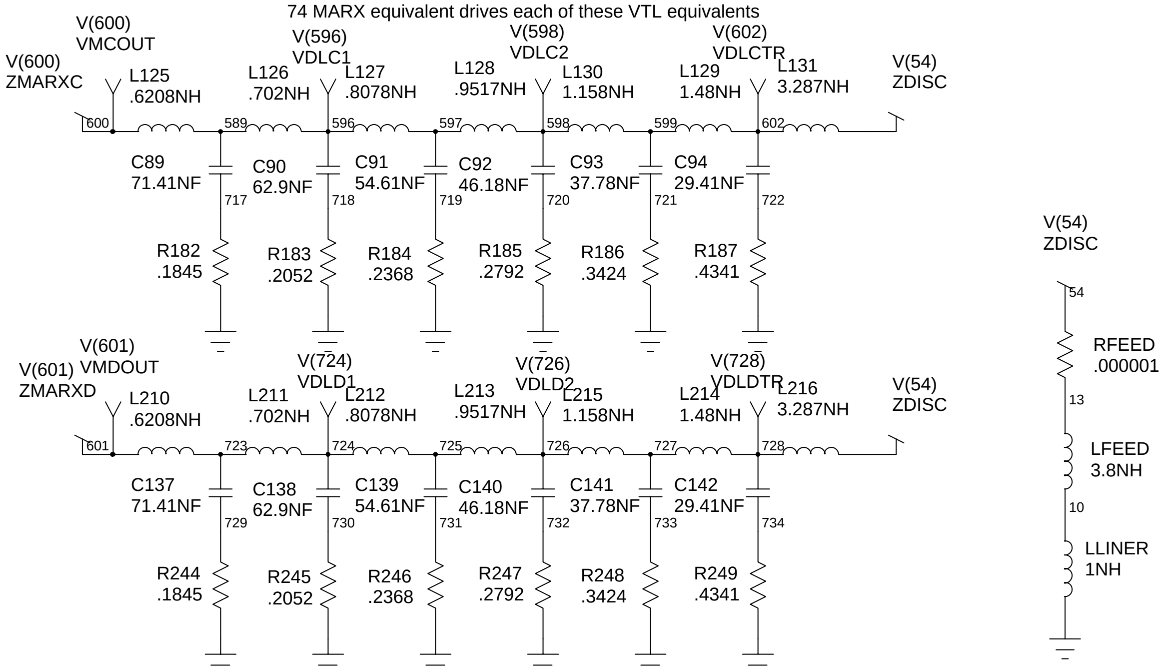
balence same in air and oil models 3.8nh feed + 1nh liner

VTL loses modeled as critically damped RLC segments

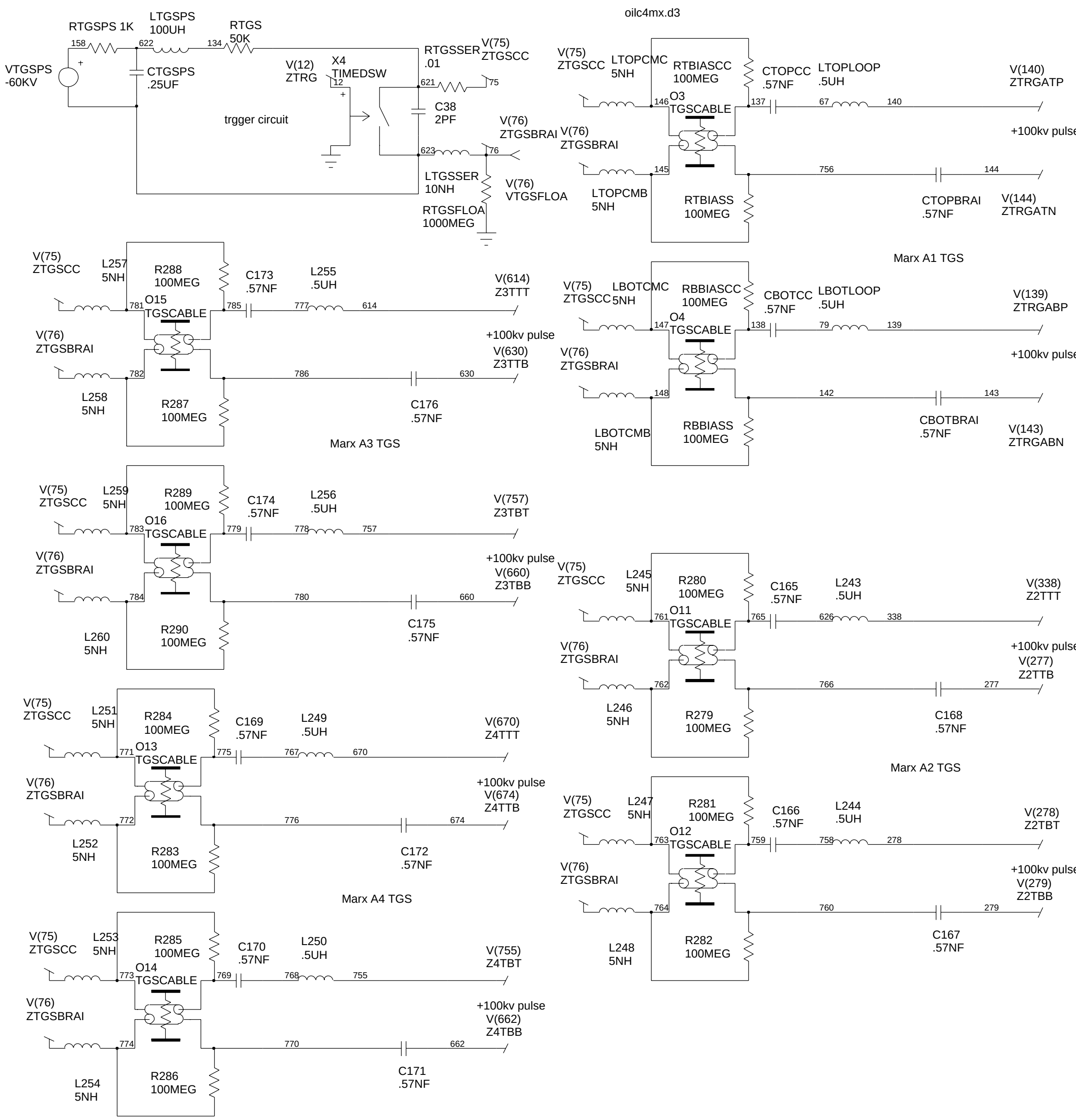


4 individual Marx drive this one VTL

74 MARX equivalent drives each of these VTL equivalents



Sheet 2. VTL, transition section, and static load (oil4mx.d2)



Sheet 3. Trigger circuit (oil4mx.d3)